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Internet Access to a Fluid Power Mechatronics Laboratory

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***Abstract*—System dynamics is a course that needs physical experiments to realistically represent behaviors of mechatronic systems to students. This paper describes how experiments in fluid power for motion control can be provided over the internet. A hydraulic system was chosen because this important example is absent from hands on experiments in traditional laboratories. Internet access allows the equipment to be fully utilized without the expense, hazards or scheduling conflicts otherwise encountered. The system and its software are described and representative results from experiments are shown.**

***Index terms*—laboratory, hydraulics, internet, mechatronic**

I. INTRODUCTION

System dynamics and control theory are required in most accredited undergraduate mechanical engineering curricula. Typically, this course covers topics such as: modeling of mechanical, electrical, fluid, and thermal systems, feedback control, time response analysis and design, and frequency response analysis and design. Students are expected to draw upon their knowledge of rigid body dynamics, differential equations, instrumentation, computer science, and electrical circuits in order to accomplish the course objectives. Student interaction with dynamic systems is usually confined to the theoretical domain. Idealized linear models and simulations are the extent of applications of control theory. Access to simple hardware or a hands-on experiment is typically limited by the availability of experimental equipment and a lack of supervised laboratory time. A remote access laboratory with unlimited accessibility would alleviate this problem. In addition, exposing students to the full range of physical systems and energy domains studied in the course is practically impossible if they must have physical access to hardware.

One area of study that has traditionally received little attention in US undergraduate engineering curricula is fluid power technology. Fluid power experiments are uncommon in academic settings due to relatively high equipment costs, the large size of the actuators, the danger associated with powerful actuators, and the inevitable mess produced by fluid systems. Fluid power systems, namely hydraulic systems, are used extensively in industrial equipment, however. Implementing controls for these hydraulically actuated processes is common outside of undergraduate academia. The unbalance between education on control of hydraulic systems and demand for engineers knowledgeable on the subject of hydraulic control makes fluid power technology an excellent candidate for an area of educational improvement.

The goal of this project was to provide the undergraduate students with a system dynamics and control course that has a strong connection to real-world applications and uses real physical hardware. The course modifications were desired without a dramatic increase in the demand for financial support or manpower.

II. PLAN FOR MEETING THE OBJECTIVES

The objectives cited above were to be met by developing a multiple degree-of-freedom, hydraulically actuated, robotic manipulator resembling a real-world motion control system, i.e. a fork-lift truck. This device is named the Hydraulically Actuated Lifter. (HAL) This manipulator was to be controlled from any remote computer capable of accessing the Internet to form the Virtual Access Laboratory (VAL). More detailed objectives were developed regarding the nature of the experiments and the principles to be illustrated by the experiments in the remote access laboratory. The following list describes the different experiments that were required of the remote access laboratory.

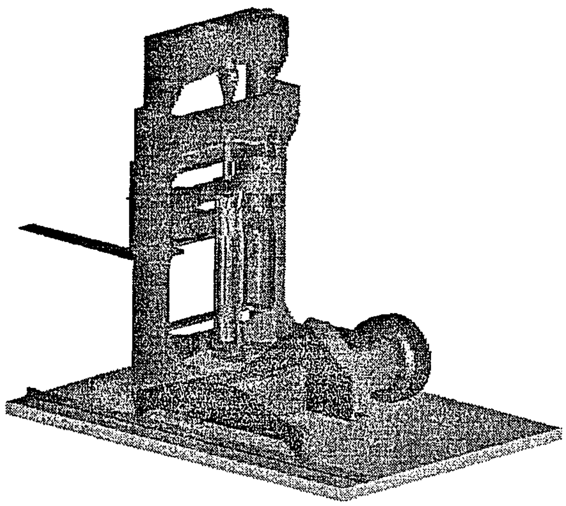
- Familiarization with experimental equipment
- System identification using force response
- System identification using position response with proportional feedback control (step input and sinusoidal input)
- PID control with the ability to change the gain values
- Trajectory planning and following

These experiments were chosen in order to demonstrate the following engineering principles and concepts associated with system dynamics and controls.

- Time constants, natural frequencies, and damping ratios (Exps: 1,2,3,4)
- Steady state error (Exps: 3,4,5)
- Stability, instability, and stability margin (Exps: 4)
- Feedback effects (Exp: 3)
- Actuator and sensor capabilities and limitations
- Frequency and time response (Exps: 2,3)
- Nonlinear effects (Exps: 2,3,4,5)
- Disturbance input effects
- Representation of system behavior (Exps: 2,3)

Exposing students to real physical systems provides them with opportunities and experiences otherwise unobtainable with simulations. Students encounter the challenges associated with estimating model parameters and identifying mathematical models for physical system components. In addition, students have the opportunity to compare theoretical data from computer simulations to experimental data from a real system.

III. MECHANISM, ACTUATION AND SENSORS



:*Figure 1.* **The Hydraulically Actuated Lifter (HAL).**

Figure 1 shows an overview of the Hydraulically Actuated Lifter (HAL). The details of the mechanism design are contained in Rouse[1]. To use industrial scale equipment it was necessary to create a fairly large device. An imitation of a fork-lift truck was chosen because it has a degree of realism and yet is not overly large. We preferred two substantially different type of actuators and the lift and translation motion provided this feature. The chain drive found on a duplexed mast driven by a piston/cylinder was replicated for realism and provides a realistic gravity constraint on downward acceleration in experiments. The drive wheel provides a slip constraint. Tilt of the mast was considered but it added more cost without much gain in educational value. In a natural setting the lifting of different loads provides variation in conditions of operation realistic to students.

A summary of sensors and actuators specified is below.

- Lift actuation: piston/cylinder
- Lift sensor: Magnetostricive, internal to cylinder.
- Lift sensor (force): strain gauge load cell
- Drive actuation: hydraulic motor
- Drive sensing: string potentiometer
- Hydraulic valves: electrohydraulic servovalves

The use of electrohydraulic servovalves is an unrealistic choice for small fork-lifts, but electronic actuation was necessary to enable access over the internet. A pressure sensor was not provided in the initial design but is planned as an add-on.

A commercial hydraulic power supply was chosen based on duty cycle that could be extensive and based on the possibility of building two units powered by the same supply. It can be turned on and off by the computer.

IV. REMOTE ACCESS SOFTWARE

There are two main software components of the remote access laboratory, namely the client and server programs. The client program serves as the student's interface to the experiment. Access to the program is time restricted. The server program is run locally on the server computer. These programs can communicate with each other via Georgia Tech's campus network or the Internet. A brief discussion of these two software components is given in the next two sections. For a detailed analysis of the software and communication scheme refer to Koeppen[2].

A. Client Software and Web Access

For this laboratory, the client-side software is a Java applet. Applets are similar to applications, but are run from a Web page. This applet provides the user with a Graphical User Interface (GUI). The GUI provides a variety of buttons and check boxes for student input including options such as selecting which experiment to run, what type of system input to provide, and the desired compensator gain values for a PID controller.

Access to the client program, and time slot reservations, is done on the Internet via the World Wide Web. Using WebCT, only students enrolled in the class will be granted access to the class homepage; furthermore, only students with the appropriate reservations will be allowed access to the Internet server containing the client applet. WebCT is not the ideal approach and access control directly on the server is being considered. The applet is served from the same computer that runs the actual experiments. This is necessary due to security restrictions that are inherent to applets that forbid socket connections to Internet sites other than the one that served the Web page that includes the applet. Applets are also incapable of performing read/write operations to the user's computer. Access to a file containing the experimental data is granted to the user upon completion of the experiment.

Once the applet is accessed, students must establish a socket connection to the server, and run the experiment. The server software will close this socket connection after the student's allotted time has expired, if the student has not already done so.

A listing of the necessary steps involved in completing an experiment is included in Table 1.

Table 1. **Sequence of Actions in a Typical Lab Cycle.**

Browser/WebCT Server
1. Enter WebCT
2. Sign up for access time
3. Log off WebCT
4. Manual grouping of students for access times
5. Log on to WebCT
6. Access instruction page
Beginning of release time for access
7. Access experiment page on control server
Browser/Control Server
8. Java applet is transferred to browser
9. Student sets up experiment through applet
10. Applet establishes socket connection
11. Student runs experiment
12. Student views and judges results. Repeat if needed
13. Student saves results for post processing
14. Close socket connection
15. Return to WebCT
End of release time for access
16. Perform other WebCT functions if desired
17. Log off WebCT

B. Server and Real Time Control Software

In order to achieve deterministic real-time control using Windows NT, Hyperkernel was used to interface with the manipulator. CPU time and memory resources are partitioned between Windows NT and Hyperkernel. Communication between the programs in the two partitions occurs via shared memory, as shown in Figure 2.

Hyperkernel has its own scheduler and its own internal kernel. In practice, the CPU time allotted for Windows NT and Hyperkernel is proportioned into alternating 250 microsecond segments. Because of this duality, two sets of code were written in C++. This allows the real time control of the experiment to proceed without the uncertain delays of the Windows NT scheduled tasks.

The server code written for Windows NT handles the socket connection with the client and is responsible for starting the Hyperkernel code. The Hyperkernel code, modeled after code written by CAMotion Inc., is responsible for the real-time control, and contains a main thread, an Interrupt Service Routine (ISR), and a thread used for input and output. Both Windows NT and Hyperkernel programs are run on the computer that acts as the Internet server for the client applet. Using Hyperkernel APIs, the ISR signals the input/output thread to send and receive the next data values. Data received from the client, such as the desired input type and gain values, is passed from Windows NT to Hyperkernel through shared memory. This communication path is also show in Figure 2. Code has been added to ensure the integrity of various structures passed via shared memory in spite of switching between NT and Hyperkernel. Also, checks for the range of data are performed to avoid dangerous values entered by the user.

C. Live Camera for Visual Feedback

A camera is focused on the experiment in order to give the student an intuitive sense of what is happening. An inexpensive web camera is sufficient for the current transmission of the images over MicroSoft NetMeetings. It is preferable to move to streaming video for a faster frame rate using Real Video or other free software. This still avoids any software purchases by the student. Currently, all software except for the client runs on one Intel processor. It seems wise to shift the streaming of video to another computer.

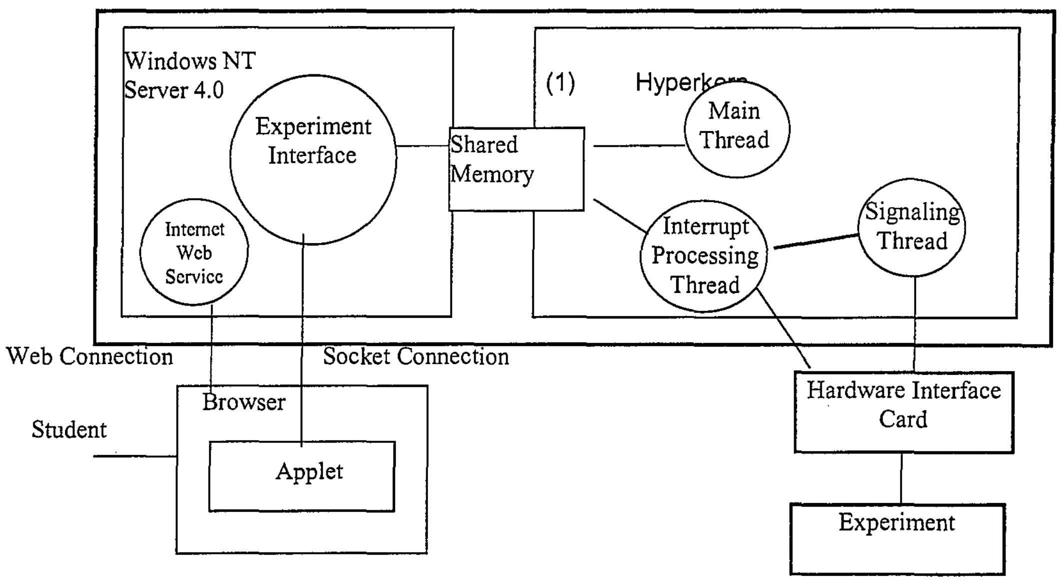


Figure 2. **Interrelation of Software for display, serving and control for the Virtual Access Laboratory (VAL).**

V. EXPERIMENTAL RESULTS

Several experiments were run both locally and from remote locations to evaluate the performance of HAL and VAL. The following sections present data collected from these experiments. The experimental data presented is representative of what student would retrieve after performing a typical experiment.

A. *Step Response - Piston*

The dynamic response of a system to a step input is one of the most common experiments in simulations and on hardware. In order to perform a position step response experiment on a hydraulic system it is necessary to run the actuator in a closed loop. In an open loop configuration, hydraulic actuators respond like pure integrators and produce an unstable output from a constant input.

The piston was given a step input to a displacement of four inches and had an initial displacement of two inches. A proportional controller with a gain value equal to one was used. For this particular experiment, HAL was not carrying a payload or an end effector. The desired and measured positions of the piston are shown in Figure 3.

The response resembles the step response of a typical first order system. Therefore, the closed loop system was estimated as a first order system with a time-constant equal to 1.5 seconds. The time constant was determined by estimating the time value at the intersection point between the initial slope of the response data and the line representing the desired position. The resulting closed loop transfer function (H_{CL1}, indicating a closed loop, first-order transfer function), relating the reference and output positions, is shown in the equation

$$H_{CL1} = \frac{1}{1.5s+1}$$

Figure 3 shows the experimental step response data plotted along with the simulation results from the transfer function shown above.

Figure 3 shows that a first-order approximation might be acceptable for the majority of the rise time, but the simulation and experimental data begin to deviate after time equals two seconds. The experimental data shows that the piston very slowly approaches the desired value after it reaches a displacement of about 3.5 inches. This condition could be due to friction between the valve body and spool, friction within the piston, and leakage flow in the valve, which increases as the valve reaches the null position. The valve does approach the null position as the piston nears the desired step value, because the error signal controlling valve displacement decreases to near zero. This is the kind of discrepancy a student should learn to interpret in experiments on physical hardware.

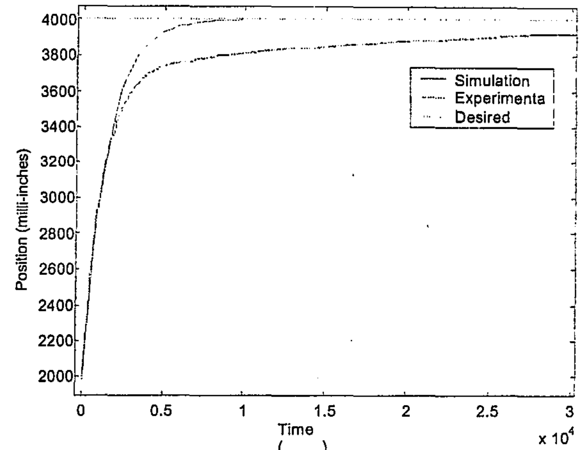


Figure 3. **Comparison of Piston Response (bottom curve) to Simulation result (top curve) for Step input (straight line).**

B. *Step Response - Motor*

The closed loop response of the motor to a step input was also investigated. The motor was given a command to step to four inches from its initial position of approximately two inches. Again, HAL was not carrying a payload or an end effector. The desired and measured data are shown in Figure 4. Of critical educational value is that the step response is not perfect in either case. This is what experiments provide that simulation will not: experiences in the real world. In this case a large steady state error exists and a vibratory behavior occurs due to backlash in the motor drive. With higher gains this will lead to a limit cycle.

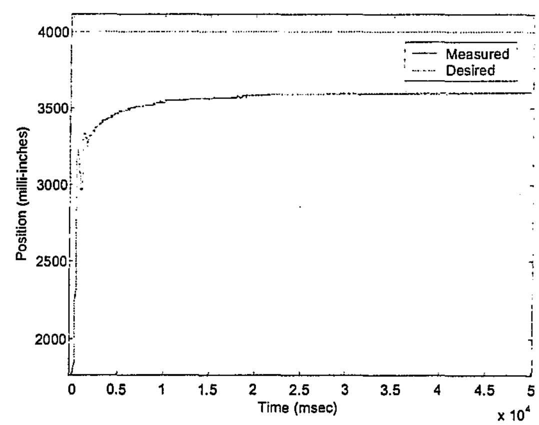


Figure 4. **Response of Hydraulic Motor to Step input (straight line).**

VI. FREQUENCY RESPONSE

A. *Piston Frequency Response*

Experimental Bode plots were derived for the piston by applying a swept sine wave command with an amplitude of

2 inches and a mean position value of 12 inches. The frequency was linearly swept from 0 to 16 Hz over a total time of 50 seconds. Six runs of this experiment were performed and the frequency responses were averaged to produce the Bode plot in Figure 5.. Also included in Figure 5 is the theoretical Bode plot of the third-order model of the piston, as commonly used to model this hydraulic system

The experimental and theoretical Bode plots are fairly consistent with one another, indicating that Equation 6.5 is a reasonable model for the piston and valve over this frequency range. At frequencies greater than about 16 Hz, noise signals begin to dominate the response data..

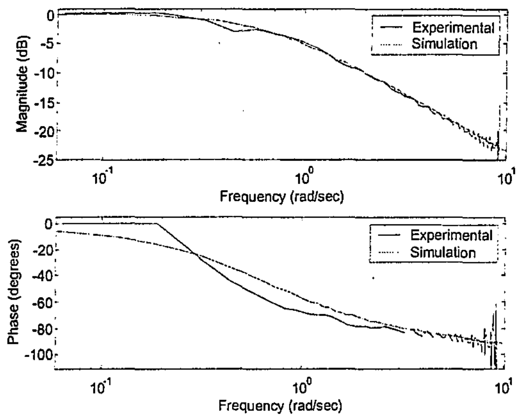


Figure 5. **Bode Plot of Piston performance with Theoretical Curve for a Third Order System.**

B. Motor Frequency Response

The presence of the backlash in the motor limited the effectiveness of linear system identification techniques. The motor was given a swept sinusoidal input from 0 to 16 Hz with an amplitude of 2 inches. Again, the experiment was run in closed loop with a proportional gain of one. Figure 6 shows the input signal position signal and the actual position output in the drive direction.

The shape of the measured output position curve is typical for backlash nonlinearities. This nonlinearity might provide an opportunity to introduce undergraduates to the effects of nonlinearities in dynamic systems. Specifications on the hydraulic motor backlash were not available from the manufacturer. In the future, the backlash could be analyzed and modeled using describing function analysis techniques.

VII. Trapezoidal Velocity Profile

A trajectory planning experiment was run in which four consecutive trapezoidal velocity profiles were used to move the tip of HAL along a box shaped path. Due to lack of space the plots of these experiments are not included here.

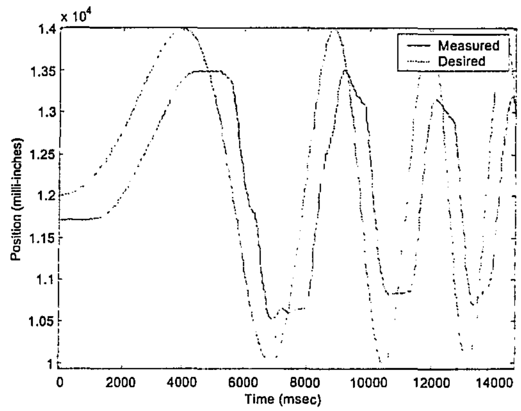


Figure 6. **Time Response of Motor to a Swept Sine input.**

VIII. Project Cost

Overall, the remote access laboratory cost approximately $28,000. This figure includes all equipment, parts, and components used in the laboratory, but does not include machine shop labor or student labor costs. Table 2 provides overview of approximate project cost and a more detailed look at areas of particular interest.

IX. Future Work

Integrating the remote access laboratory into a course at Georgia Tech will provide excellent feedback about the advantages and disadvantages of VAL. Students should run experiments on HAL and offer suggestions on how to improve the effectiveness of the laboratory experience.

Several potential improvements on the system have been mentioned throughout the paper. The following list outlines other potential improvements and modifications that could be done to expand the operating capabilities of the laboratory.

- A pressure transducer could be used to obtain dynamic reponse data on the actuators and the hydraulic power unit pump.
- Accelerometers could be mounted on HAL to analyze vibrations or determine component position.
- An encoder could be fitted to the drive wheel to measure motor position, velocity, etc.
- The cross-over pressure relief on the hydraulic motor could be adjusted to modify the damping characteristics of the motor.
- Experiments could be performed to analyze the effects of slip between the drive tire and platform.

<u>Safety Issues</u>

There is no limit to the number of safety features that could be added to the remote access laboratory. Regardless of the safety measures in place, it is always important to understand the danger involved when operating hydraulic manipulators. Care should always be taken to clear the operating area before operation begins. The following list outlines a number of possible safety improvements that could be made to the remote access laboratory. By no means does this list represents all the safety features needed. The details regarding safety requirements will depend on the location of HAL and the manner in which it is used. In particular a safety enclosure capable of detecting a breach in the safety wall and triggering a system shutdown must be installed. With this provision the operation will be far safer than normal laboratories with students on site.

X. SUMMARY

The remote access laboratory is capable of providing students with practically unlimited access to standard system dynamics and controls experiments on a hydraulically actuated manipulator. HAL was designed to emulate industrial motion control system in order to provide students with experience on real-world hardware.

The remote access laboratory is capable of performing all of the desired experiments: introductory experiment, PID control, system identification, and trajectory following. Concepts such as time constants, steady-state error, natural frequency, and damping ratio can be demonstrated through experiments with HAL.

The steady-state and dynamic operating characteristics of HAL are indicative of industrial hydraulic systems. The hydraulic piston exhibits characteristics that closely match theoretical models, while the hydraulic motor exhibits more complicated nonlinear dynamics. This variation in actuator characteristics will provide students with a more complete understanding of system dynamics.

Table 2. **Summary of Project Costs.**

Category and Item	Cost ($)
Mechanical System	4505
Hydraulic System	
Power unit	7000
Hydraulic fluid	220
Hydraulic plumbing materials and labor	2800
Hydraulic motor	150
Servovalve for motor	1600
Cross-over pressure relief	380
Piston, servovalve, and LDT	4800
Other	100
Subtotal	**17050**
Electrical System	
Server computer	1570
Internet camera	80
Servo-to-go I/O Card	890
Load cell	665
Amplifier for load cell	265
Cable and connector for load cell	60
Linear resistive transducer	170
Signal conditioning card for valve controlling the motor	365
Cable and connector on motor servovalve	75
Signal conditioning card for valve controlling the piston	365
Cable and connector on piston servovalve	75
Electrical parts and labor to wire hydraulic power unit	720
Shielded cable	60
Electrical connectors, wire, and shrink wrap	50
Other	250
Subtotal	**5660**
Other (tools, drill bits, lathe bits, etc.)	**250**
Grand Total	**27465**

References

[1] Rouse, Matthew, "Design and Evaluation of a Remote Access Hydraulic Manipulator for System Dynamics and Controls Education," MS Thesis, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, USA February, 2001.

[2] Koeppen, Kyle, "Virtual Access Hydraulics Experiment for System Dynamics and Controls Education," MS Thesis, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA. USA. January, 2001.